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Nanoparticles Enhanced Phase Change Material (NPCM) as Heat Storage in Solar Still Application for Productivity Enhancement

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Abstract

Whereas other researchers used various active and passive techniques to improve the productivity of solar still, this paper uses nanoparticles impregnated in phase change material (NPCM) for productivity enhancement. The solar still is fabricated individually with phase change material (PCM) and NPCM and analyzed both experimentally and theoretically. It is found that the solar still with PCM yielded 1.96 kg/0.5m² whereas the solar still with NPCM yielded 2.64 kg/0.5m². There was 35% improvement in productivity observed in solar still with NPCM as against solar still with PCM. The experimental results were validated with the predicted results and the discrepancy was found to be $\pm 10\%$. Hence it is concluded that NPCM has better potential than PCM for solar still applications

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Keywords: energy storage; solar still; phase change material; nano particles; productivity; paraffin

1. Introduction

Desalination is the only remedy to meet the growing demand for fresh water. There are various desalination techniques [1], among them solar still is one of the ancient economic technique to desalinate the saline water. There are various active and passive methods to increase the distillate yield in solar still [1]. Latent heat energy storage is one such methods which uses phase change materials (PCM) for energy storage. The main drawback of PCM is its thermal conductivity and energy storage density. To overcome this nanoparticles are being used in various applications.

Very few literatures have been reported using PCM in solar still application. Shalaby et al. [2] used paraffin in solar still and found that it improves the distillate yield by 12%. Kabeel and Abdelgaied [3] used paraffin in solar still and obtained 67.18% increase in productivity than that of the conventional stills. Ansari et al. [4] used paraffin in the solar still and achieved productivity of about 4.5 l/m². Dashtban and Tabrizi [5] used paraffin and achieved productivity of about 6.7 l/m². Mousa and Gujarathi [6] used paraffin as latent heat energy storage material in solar

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still application and achieved 49% increase in productivity. Sarhaddi et al. [7] used paraffin in cascade solar still and achieved the maximum energy efficiency up to 75%. However there is no literature available using nanoparticle enhanced PCM (NPCM) in solar still application. Thus the proposed work bridges the aforementioned research gap by analyzing the solar still with NPCM and comparing against PCM both experimentally and theoretically.

2. Mathematical modelling

The mathematical modeling was done by formulating energy balance equation for each components of the solar still. The schematic of solar still is depicted in [5 and 7]. The following assumptions are made:

1. Glass and water temperatures are uniform
2. Heat losses (from sides of the solar still) are negligible
3. There is no convection and temperature gradient in and throughout the PCM respectively

In the following equations the subscripts gl, w, a, sk, p, pcm, 1, 2 ins, c, ev, s and l represents glass, water, air, sky, absorber plate, PCM, heat transfer coefficient from absorber plate to water, water to glass cover, insulator, convection, evaporation, solid and liquid state respectively. The symbols A, T, I(t), α , τ , Gr, Pr, h, C, K, x' represents the area, temperature, intensity of solar radiation, absorption co-efficient, transmission co-efficient, Grashof number, Prandtl number, heat transfer co-efficient, specific heat capacity, thermal conductivity, characteristic dimension for the rectangular surface respectively.

2.1. Energy balance equation for Glass cover

The energy balance equation for glass cover is given below [7]

$$\alpha_{gl} I(t) A_{gl} + h_2 A_w (T_w - T_{gl}) = h_{c,gl-a} A_{gl} (T_{gl} - T_a) + h_{r,gl-a} A_{gl} (T_{gl} - T_{sk}) + m_{gl} c_{gl} \left(\frac{dT_{gl}}{dt} \right)$$

where α_{gl} and c_{gl} corresponds to 0.05 and 800 J/kg. $^{\circ}$ C respectively

2.2. Energy balance equation for brine water

The energy balance equation for brine water is given below [7]

$$\alpha_w I(t) A_w T_w + h_1 A_p (T_p - T_w) = h_2 A_w (T_w - T_{gl}) + m_w c_w \left(\frac{dT_w}{dt} \right)$$

$$h_1 = 0.54 \left(\frac{K_w}{x'} \right) (Gr \cdot Pr)^{0.25}$$

where x' , K_w , A_p , C_w and α_w corresponds to 1 m, 0.57 W/m 2 . $^{\circ}$ C, 1 m 2 , 4190 J/kg. $^{\circ}$ C and 0.05 respectively

2.3. Energy balance equation for Absorber plate

The energy balance equation for absorber plate is given below [7]

$$\alpha_p I(t) A_p \tau_g \tau_w = h_1 A_p (T_p - T_w) + \left(\frac{K_{pcm}}{X_{pcm}} \right) A_p (T_p - T_{pcm}) + m_p c_p \left(\frac{dT_p}{dt} \right)$$

Where the values of α_p , τ_g , τ_w , A_p , C_p , K_{pcm} , X_{pcm} , m_{pcm} are 0.9, 0.9, 0.95, 1 m 2 , 896 J/kg. $^{\circ}$ C, 0.26 W/m 2 . $^{\circ}$ C, 0.02m and 9 kg respectively

2.4. Energy balance equation for PCM

The melting point of PCM and NPCM is 63.5 and 59 $^{\circ}$ C respectively. The energy balance equation for PCM when the temperature of PCM is less than that of melting point temperature is given by [7]

$$\left(\frac{K_{pcm}}{X_{pcm}} \right) (T_p - T_{pcm}) = \left(\frac{K_{ins}}{X_{ins}} \right) (T_{pcm} - T_a) + \frac{m_{pcm} c_{s,pcm}}{A_p} \left(\frac{dT_{pcm}}{dt} \right)$$

The energy balance equation when the PCM temperature is between melting point and incremental rise is given by [7]

$$\left(\frac{K_{pcm}}{X_{pcm}} \right) (T_p - T_{pcm}) = \left(\frac{K_{ins}}{X_{ins}} \right) (T_{pcm} - T_a) + \frac{m_{pcm} L_{pcm}}{A_p} \left(\frac{dT_{pcm}}{dt} \right)$$

The energy balance equation when the PCM temperature is more than the incremental rise of the melting point is given by [7]

$$\left(\frac{K_{pcm}}{X_{pcm}} \right) (T_p - T_{pcm}) = \left(\frac{K_{ins}}{X_{ins}} \right) (T_{pcm} - T_a) + \frac{m_{pcm} c_{l,pcm}}{A_p} \left(\frac{dT_{pcm}}{dt} \right)$$

where the incremental rise, $c_{s,pcm}$, $c_{l,pcm}$, L_{pcm} , K_{pcm} , X_{pcm} , K_{ins} , X_{ins} values are 3 $^{\circ}$, 2.95 kJ/kg. $^{\circ}$ C, 2.51 kJ/kg. $^{\circ}$ C, 102 kJ/kg, 0.26 W/m 2 . $^{\circ}$ C, 0.02 m, 0.033 W/m 2 . $^{\circ}$ C and 0.03 m respectively. The same equation will be used for NPCM,

but only physical properties of NPCM varies i.e, the L_{npcm} , K_{npcm} corresponds to 168 kJ/kg and 0.335 W/m².°C respectively. Productivity can be calculated by

$$m_{ev} = \frac{h_{ev} A_w (T_w - T_{gl})^{3600}}{h_{fg}}$$

where h_{fg} is the latent heat of vaporization of water [7]. The above non-linear differential equation was solved by fourth order Runge-Kutta method using MATLAB software.

3. Materials and methods

Paraffin and copper oxide nanoparticles were purchased from Merk Millipore and SRL, India respectively. SDBS (Sodium dodecylbenzene sulfonate) was purchased from Sigma- Aldrich, USA and used as surfactant during the preparation of NPCM. 0.3 weight% of copper oxide nanoparticles are impregnated in paraffin individually to form NPCM. The experiments were carried out in the Institute for Energy Studies, Department of Mechanical Engineering, Anna University, Chennai, India. The solar still was fabricated with Al-6061 of 0.5m². The bottom and sides were insulated using thermocol. The pictorial representation is depicted in Fig. 2.a. Brine water of about 10 kg is poured inside the setup. A reservoir of about 2 cm height was fabricated below the absorber plate to hold the storage material. A transparent glass cover (2.5 mm thickness) with inclination of about 13°.

4. Results and discussion

The variation of solar intensity and wind velocity against time is depicted in Fig. 1.b. The solar radiation starts by 8:00 AM and attains maximum intensity of about 830 W/m². It is inferred that the intensity profile throughout the day was homogenous. The comparison of various temperatures of solar still with PCM and NPCM is depicted in Fig. 1.a. It is found that the water temperature of solar still with PCM was higher than that of the water in solar still with NPCM till 14:00 PM and after 14:00 PM this gets reverse. This is because during charging water acts as a source to PCM and during discharging water acts as a sink such that it absorbs the heat from PCM for evaporation.

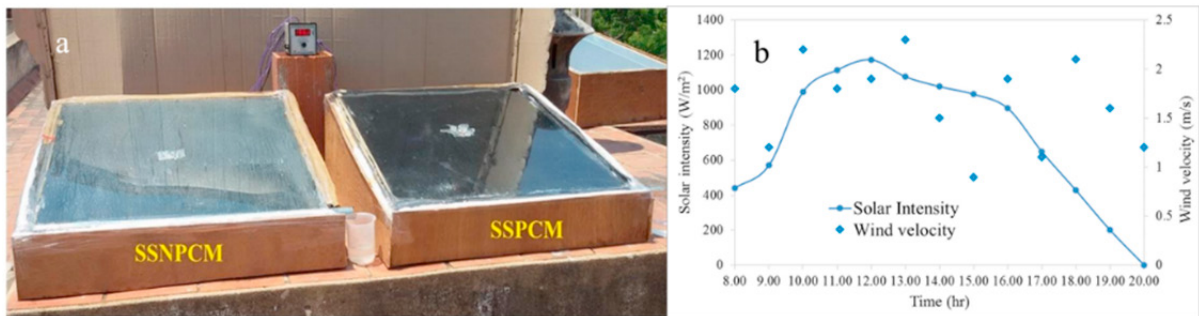


Fig. 1 (a) solar still with PCM (SSPCM) and NPCM (SSNPCM); (b) Wind speed and solar intensity variation

Impregnating nanoparticles in PCM enhances the thermal conductivity and energy storage density of the PCM. The PCM temperature of solar still with PCM and NPCM was compared and depicted in Fig. 2. It was found that the temperature of NPCM was higher than that of PCM till 13:30 and after 13:30, NPCM temperature leads the PCM temperature and this is because of the higher thermal conductivity of NPCM than that of PCM during charging. During discharging the solidification rate was low as compared to solar still with PCM. The glass temperature of PCM was always higher than that of NPCM and this phenomena is quite common.

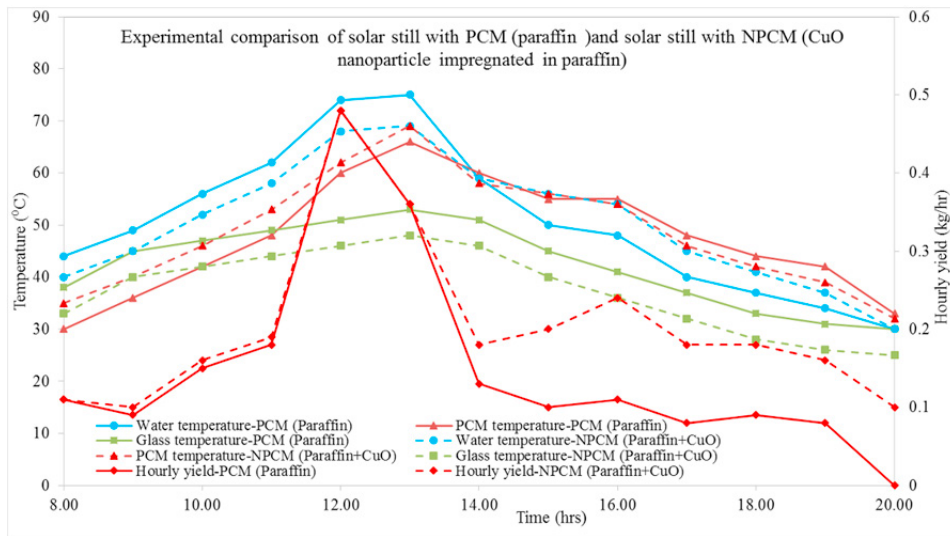


Fig. 2. Experimental comparison of solar still with PCM and solar still with NPCM

It is inferred that the hourly productivity of solar still with NPCM is higher than that of the solar still with PCM. It is found that initially (up to 12:00 PM), there was only a minor difference in the productivity of two stills, as the time proceeds, discharging of PCM and NPCM occurs, the still with NPCM produces more condensate hourly as its melting and solidification rate was higher than that of PCM. There was 60% increase in hourly yield achieved with solar still with NPCM than that of PCM from 13:00 PM to 20:00 PM. During solidification process (after 13:00 PM), the storage material starts to release its heat in terms of latent heat, since the latent heat of NPCM is more than that of PCM, the amount of heat transferred to water is high which in turn increases the condensate yield. To conclude, improvement in thermal conductivity and latent heat energy storage capacity of NPCM improved the productivity.

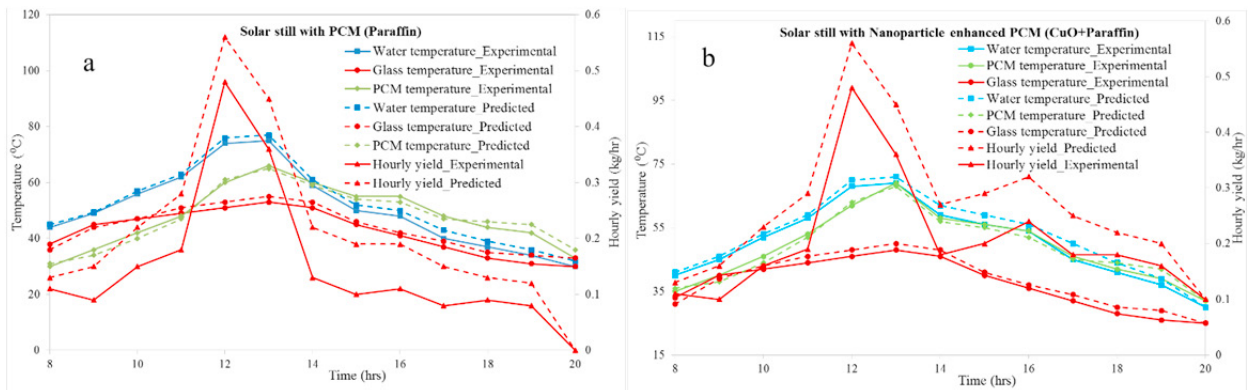


Fig. 3. (a) Validation of solar still with PCM; (b) Validation of solar still with NPCM

The experiments results were validated with the predicted results and depicted in Fig. 3.a and 3. b. The discrepancy was only about $\pm 10\%$. From the predicted results, there was 26% increase in productivity observed in solar still with NPCM than that of PCM. The experimental cumulative yield of solar still with PCM and NPCM is depicted in Fig. 4 and it was found to be 1.96 and 2.64 kg/0.5m² respectively. There was 35% improvement observed in the overall daily distillate yield of solar still with PCM than that of the solar still with NPCM.

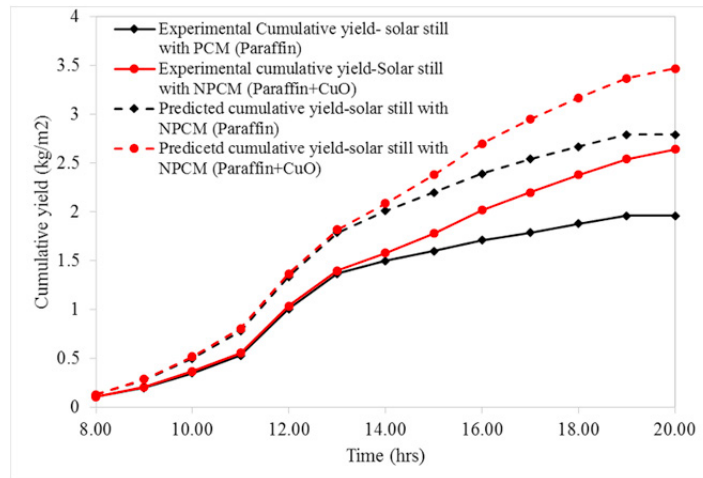


Fig. 4. Comparison of cumulative yield of experimental and predicted results

Hence it is evident that, impregnation of nanoparticles in phase change material enhances the productivity of the solar still as compared to solar still with only phase change materials as a latent heat storage medium.

5. Conclusion

Nanoparticles (CuO) are impregnated in paraffin and used as a latent heat energy storage medium in solar still for desalination applications. Based on the results following conclusions were made

1. Solar still with CuO nanoparticles enhanced phase change materials showed 35% improvement in the productivity than that of the solar still with only phase change materials
2. The daily productivity of solar still with phase change materials was 1.96 kg/0.5m² whereas the solar still with CuO nanoparticles enhanced phase change materials yielded 2.64 kg/0.5m².
3. Impregnation of CuO nanoparticles in phase change materials has better potential as against the use of virgin phase change material in solar still applications

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